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Designing Efficient Infrastructural Investment and Asset Transfer Mechanisms in Humanitarian Supply Chains

We analyze the efficacy of different asset transfer mechanisms and provide policy recommendations for the design of humanitarian supply chains. As a part of their preparedness effort, humanitarian organizations often make decisions on resource investments ex-ante because doing so allows for rapid response if an adverse event occurs. However, programs typically operate under funding constraints and donor earmarks with autonomous decision-making authority resting with the local entities, which makes the design of efficient humanitarian supply chains a challenging problem. We formulate this problem in an agency setting with two independent aid programs, where different asset transfer mechanisms are considered and where investments in resources are of two types: a primary resource that is needed for providing the aid, and infrastructural investments that improve the operation of the aid program in using the primary resource. The primary resource is modeled as either a divisible or indivisible good, and is acquired from earmarked donations. We show that allowing aid programs the flexibility of transferring primary resources improves the efficiency of the system by yielding greater social welfare than when this flexibility does not exist. More importantly, we show that a central entity that can acquire primary resources from one program and sell them to the other program can further improve system efficiency by providing a mechanism that facilitates the transfer of primary resources and eliminates losses from gaming. This outcome is achieved without depriving the individual aid programs of their decision-making autonomy while maintaining the constraints under which they operate. We find that outcomes with centralized resource transfer but decentralized infrastructural investments by the aid programs are the same as with a completely centralized system (where both resource transfer and infrastructural investments are centralized).

Key words: asset transfer; humanitarian logistics; supply chain design
History:

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1. Introduction

The field of humanitarian logistics has recently received greater attention as scholars recognize similarities and differences in the specific needs of supply chains in response to disasters vis-a-vis supply chains in the private sector (Van Wassenhove 2006, Gupta 2011, Holguin-Veras et al. 2012). One important difference in the nature of these supply chains is the set of objectives targeted by profit versus nonprofit organizations (Tomasini and Van Wassenhove 2009a). Yet there are many other differences between the design requirements of humanitarian logistics systems and those of corporate supply chains (Holguin-Veras et al. 2012). Logistics involved in disaster response are typically reactive and are set up temporarily with specific functional elements in mind (Jahre et al. 2009), but they still require extensive planning and coordination for successful operation

(Balcik et al. 2010). Such planning and coordination activities are often needed in advance of the actual events and must bear potential factors (e.g., geography, regional sensitivity to future events) in mind. Thus, the planning of humanitarian logistics systems has three main focus areas: preparedness, response, and collaboration (Tomasini and Van Wassenhove 2009b).

To facilitate rapid response to adverse events such as natural disasters, it is imperative that aid programs establish their resource needs as early as possible and acquire their primary resources. An obvious example would be transportation assets like trucks, planes, and earth moving equipment, which are large and expensive resources, and have to be adapted to the various situations in which their deployment is an appropriate response. Other examples of primary resources could be pre-positioned relief items, where the decisions to invest in these primary resources are made based on earmarked donations. Note that we use the terms "primary resources" and "assets" interchangeably in the paper. The aid programs are also required to invest in an infrastructure to make good use of these primary resources, e.g., logistics or maintenance skills, driver training or warehouse operating equipment. Resource planning and allocation are therefore important aspects of the preparedness and response activities of aid organizations.

In this paper, we analyze the allocation and use of expensive resources by humanitarian logistics programs under the context-specific field conditions that make these activities a complex and challenging problem. First, in contrast to corporate supply chains (which are financed by revenues from ongoing operations) and to entrepreneurial ventures (which are financed from private and corporate venture capital), aid programs typically finance their operations using donations from various government and non-government organizations and/or individuals . Second, if a donor has provided resources to an organization that is addressing some particular situation, then the donor likely and reasonably expects that the resources will be used for that situation. In this way the funding for resources is "earmarked", which makes it difficult for aid programs to share or pool resources (ICRC 2011)[1]. We analyze a set of transfer mechanisms and ownership structures for aid programs that operate under these constraints, and we investigate the efficacy of different mechanisms for achieving the benefits of collaboration.

To illustrate the types of situations modeled in this paper, consider the following context. Given that Indonesia is one of the most disaster-prone areas in the world, humanitarian organizations need to design their supply networks such that when disaster strikes, response can be fast. This means

[1] The ICRC (2011) report states that donors can earmark donations based on the country of their choice and for an activity of their choice, and the International Committee of the Red Cross provides a list of programs currently being conducted for this purpose.

establishing a logistical hub in the region with a warehouse where relief items can be pre-positioned, transportation assets like helicopters and trucks can be stationed and maintained, and logisticians can be trained. These supply network design decisions, preparedness in humanitarian speak, are mostly taken under rather severe budget constraints. Moreover, donations are often earmarked, so collaboration with other parties is far from obvious (Loescher 2001). Clearly, humanitarian organizations with different mandates, religious or country affiliations, may not be allowed to share or pool resources. But even a single organization like the International Federation of Red Cross and Red Crescent Societies (IFRC) can be strongly decentralized with independent National Societies receiving earmarked donations from the respective local governments. Another very decentralized organization is World Vision International (WVI). Its aid programs are funded by donors who may allocate a budget for five years to treat malaria in a province of Kenya. The program would be run by doctors, deal with hundreds of villages, and its budget may or may not include a provision for the procurement of vehicles and spare parts. There may be other WVI aid programs in the same region, sponsored by different donors and dealing with other issues like schooling or sanitation. The WVI programs are run independently and typically the vehicles for the malaria program are not supposed to be used to help out another program, i.e. they are strictly earmarked. In emergency situations sometimes vehicle transfers are allowed but the administrative procedures to make the flexibility possible are long and tedious, i.e. may take several weeks or more. In short, the humanitarian world deals with scarcity of resources, decentralized decision-making and earmarked donations. These conditions severely constrain their actions. Note that these conditions are typically not an issue in commercial supply chains. Unfortunately most, if not all humanitarian supply chain literature ignores these key characteristics and assumes unlimited resources, free allocation and centralized decision-making.

In this paper, we shall ask the following questions. Can mechanisms be designed to maintain the need for earmarking of donations and autonomous decision-making by individual aid programs, and yet maximize the efficiency of humanitarian aid programs? What is the nature of such mechanisms? Can these mechanisms obtain the coordinated solution to the joint problem of multiple aid organizations? What is the role of central planning agents in such systems?

To study these questions, we use a stylized model to formulate the problem of two aid programs in three different settings: (1) when no transfer of primary resources is allowed between the aid programs; (2) when each aid program is allowed to transfer its primary assets to another program (provided the other program needs the resource and the program that owns it does not); and (3) when each aid program has the option to sell the primary asset to a central entity if it does not need it; the central entity can then sell the primary asset to the other aid program. Each program procures its primary resource using earmarked donations. We also model each program as making upfront program-specific infrastructural investments to facilitate effective use of the primary resource. An example would be setting up a fleet management unit to maintain vehicles, manage spare-parts inventories, and train mechanics. The operational efficiency of primary assets like trucks for deployment and support will be increasing in the investment in the fleet management unit. Building infrastructure to effectively use primary resources has a long lead time, and hence such investments must be sunk at the beginning of the planning period. We characterize the overall utility derived by the different parties in each of these three cases and then compare the net social welfare generated by the different cases. The main contribution of this paper is as follows: in the design of humanitarian relief networks, we show that coordination entities that exist in practice perform an important role in making humanitarian relief networks efficient by facilitating the transfer of resources between different elements of the supply chain.

Our setup includes four critical, practice-driven features of the parties' humanitarian aid efforts. First, we model the primary resource as being acquired based on earmarked donations only, if the primary resource is expensive, only one party can acquire it. Second, since the funding provided by donors is earmarked, the resources cannot be jointly acquired and used by the two aid programs. Third, the programs maintain autonomy in making program-specific infrastructural investment decisions. Fourth, these programs may be part of the same humanitarian organization, or can belong to different organizations, in which case, the central entity would be an inter-organizational agency. For example, in the case of fleet management, an inter-organizational initiative like the Fleet Forum could fulfill the additional role of the central entity. The Fleet Forum was founded in 2003 as a joint initiative of the International Federation of the Red Cross and Red Crescent Societies (IFRC), the UN World Food Programme (WFP) and World Vision International (WVI). Today, the Fleet Forum is an association of more than 40 members, including NGOs, international organizations, the UN, academic institutions, donors and corporate partners (http://fleetforum.org/about/). The thrust of the paper is focused on policy recommendations for the structural design of humanitarian supply chains, and identifying conditions under which these inter-organizational agencies that facilitate the transfer of resources between different agencies make the supply chain more efficient.

Our results may be summarized as follows. We first show that in both the cases of the primary resource being either an indivisible or divisible good, a rank ordering exists between the net social welfare generated by the three cases just described, and we show that the social welfare in Case 3, with the central entity, is the highest. We also show that the net social welfare generated in this case is equal to the system-optimal social welfare, which means that it is possible for system efficiency to be maximized even under the constraints of expensive assets, donor earmarks for specific programs, and autonomy in decision-making for the aid-programs. In this scenario, the central entity either can extract all the additional surplus generated by the system or can subsidize the operating cost of the two aid programs; thus, we show that aid program designs involving a central entity can achieve a wide variety of objectives. If each program is allowed both to invest and to transfer resources, as in Case 2, then the net social welfare generated is higher than with the system in which resource transfer is not allowed (i.e., Case 1).

While the trend of increased earmarking by donors is understandable given their concerns for efficient use of the funds and corresponding desire for higher accountability and traceability we show that, earmarking primary resource funding can be counter-productive and have perverse effects. We show that efficient transfer mechanisms of the primary resource can be designed, with adequate compensation between programs, and such mechanisms eliminate the perverse effects of earmarking, yet maintain the accountability of donor funds.

We show that system designs in which individual aid programs are responsible for managing their primary resources are suboptimal and that their efficiency can be improved by facilitating the transfer of these resources. Giving each program the right to transfer the primary resource yields greater welfare benefits than denying that option, yet leads to a lower welfare than the case where resource transfer is facilitated via a centralized entity. The mechanisms developed in this paper provide normative guidelines for the optimal design of humanitarian supply chains capable of resolving the practical constraints—mainly resource constraints, earmarks, and autonomy—faced by humanitarian aid organizations.

The rest of the paper is organized as follows. In the next section, we provide an overview of the literature on investments in preparedness and response and of past studies addressing collaborative efforts in humanitarian logistics. Section 3 details the model's assumptions and formulation as well as our analysis of the model results. We conclude in Section 3.2 by summarizing the paper's contributions and outlining directions for future research.

2. Extant Literature

The literature on designing resource procurement and allocation systems can be divided into the streams directed at the functions of preparedness, response, and collaboration (Kovacs and Spens 2007, Apte 2009, Tomasini and Van Wassenhove 2009b). In the area of resource preparedness, Ozdamar et al. (2004) study the planning of emergency logistics for adverse events (e.g., future natural disasters) as a vehicle routing problem, Barabarosoglu et al. (2002) analyze helicopter logistics for disaster relief operations, and de Silva (2001) studies planning methodologies for evacuation. Salmeron and Apte (2010) explore a two-stage stochastic optimization problem; the first stage focuses on designing the supply chain for relief resources, and the second stage focuses on response logistics. Similarly, Hwang (1999) studies the design of a food distribution system that could be deployed in the event of a natural disaster. Long (1997) examines the role of information systems in determining the success of disaster relief operations. Our paper differs from this stream of literature in that we focus on the coordination of multiple aid programs to solve a more generalized problem in the design of resource procurement and allocation systems.

In the area of funding for disaster preparedness, Toyasaki and Wakolbinger (2011) report that obtaining appropriate earmarked donations for specific projects is difficult; the funding provided typically overshoots or undershoots the amount of resources required to provide relief. Concretely, this could imply a WVI program in Kenya has ample funds to buy vehicles and spare parts, while another program within the same region with a different donor may be short of funds to buy the necessary vehicles to operate effectively. Thomas (2003) identifies funding as one of the main bottlenecks in designing efficient disaster response systems. Vayrynen (2001) finds that there is a huge multiplicity of agencies with funding offering relief, and "in reality, the actions of these multiple agencies are seldom effectively coordinated and they may even undermine each other. This situation is likely to continue as the establishment of more centralized structures of governance in humanitarian relief looks unlikely". This paper addresses the need for flexible supply chain design to mitigate for the mismatch between the available resources and demand when adverse events occur in different situations.

While there are a number of studies that look at the roles of different agencies acting in response to adverse events, Loescher (2001) finds that the interests of different agencies may collide, and each agency desires to maintain decision-making autonomy to satisfy the goals of the stakeholders. Similarly, Saab et al. (2008) find that multilateral agency coordination faces many challenges, and coordination bodies that are formed to coordinate actions differ on a variety of dimensions including funding mechanisms and autonomy. Hence, the troika of funding constraints, earmarked donations and decision-making autonomy creates a specific set of challenges for designing effective humanitarian response supply chains. To the best of our knowledge, this problem has not been tackled before.

In the literature on disaster response, Murray (2005) finds that humanitarian aid programs are employing many of the best logistical practices used in corporate supply chains to reduce lead times and improve response quality. Pettit and Beresford (2005) analyze the efficiency of using a mix of military and nongovernmental aid agencies to provide emergency relief response. Several studies consider the role of infrastructure and transport connectivity in the response to natural disasters (e.g., Long and Wood 1995, Cassidy 2003). Our paper differs from that stream of literature because it focuses on the procurement and investment of resources in the preparedness phase of responding to adverse events such as natural disasters.

Finally, a number of studies consider the collaboration between different aid programs in humanitarian logistics. There is ample empirical and anecdotal evidence of precious little collaboration or coordination between different aid agencies in response to adverse events (Chomilier et al. 2003, McClintock 2005, Murray 2005). A lack of collaboration can lead to the duplication of some efforts and to insufficient scale in others (Simpson 2005). Collaboration need not be limited to nongovernmental organizations; it can also include the private sector and local communities (Tomasini and Van Wassenhove 2009a, Starr and Van Wassenhove 2011).

There are many other references to humanitarian logistics in the literature, and this number is rapidly exploding. The key point to be made here is that nearly all of this work assumes a central decision maker, little or no resource constraints, and non-earmarked funds. However, the reality of humanitarian organizations is precisely that they are almost always highly resource constrained, decentralized and subject to earmarked funding. For instance, Pedraza Martinez et al. (2010) study the alignment of incentives to coordinate a fleet of vehicles owned by different aid programs. Our paper contributes to the collaborative stream of research by analyzing the impact of differently designed mechanisms (for resource procurement and allocation) on the potential of collaboration between aid programs constrained by scarce funding and donor earmarks.

3. Model Description, Formulation, and Analysis

In this section, we describe the model setting and state our assumptions. The thrust of the paper is to make policy recommendations for the structural design of humanitarian supply chains, and not for decision support for individual relief efforts. The sequence of events in our model is as follows. There are two aid programs, $i = A, B$, and each program needs a primary resource in the event that aid must be provided. A primary resource must be lined up ex ante, before the planning horizon, because the lead time necessary to acquire primary resources can be long. In addition to procuring the primary resource, both programs must also make specific, up-front investments in building an "infrastructure" for effectively utilizing the primary resource. We use x_A and x_B to denote the respective program-specific infrastructural investments made by parties A and B. If an adverse event occurs for either party i, then providing aid services in response to that event yields the utility $u_i(x_i)$ for the affected party—provided the primary resource is at its disposal. We shall make the following four assumptions regarding the model parameters and problem constraints.

Assumption 1: Funding for primary resources is earmarked, so aid programs cannot share primary resources if they need them for their own purpose. If primary resources are not needed by an aid program, then it may transfer it to another program that may require the resources provided that the other program adequately compensates the donor program. This assumption reflects our observations in the field: donors require that funding provided for a specific purpose actually be used for that purpose.

Assumption 2: We assume that if a program has the resource and if an adverse situation occurs that requires its response, then the program will utilize the resource and not transfer it to another program (even when it could earn a surplus from doing so), thereby honoring the concerns of donors.

Assumption 3: Program i will make its own infrastructure investment decision. Assumption 3 models the decision-making autonomy of the individual aid programs.

Assumption 4: Aid program i's utility from responding to an event with the infrastructural investment x_i is given by $u_i(x_i)$; here $u_i(x_i)$ is strictly concave and increasing, $u_i(0) = 0$, and $u_i^{'}(0) = \infty$. The response utility is strictly positive; however, this assumption does not mean that the program benefits from the event. Rather, the program accrues utility from having secured a primary resource that enables it to respond immediately to any event.

3.1. Model Formulation and Analysis for indivisible primary goods

In this section, we discuss and analyze our three paradigmatic cases when the primary resource is indivisible, e.g. helicopters or small planes as the primary resource, that are needed to access two distinct regions of a country that are difficult to access by ground transport. Such resources are expensive, hence, their acquisition is limited based on the earmarked donations available to the two aid programs. For this case, to model the funding constraint, we make the additional assumption that the primary resource is so expensive that only one program has the funds to acquire it, and the other program does not. Without loss of generality, we assume a priori that Program A has the earmarked funding to purchase the resource but that Program B does not. This assumption thus reflects the scarcity of funding faced by aid agencies. Also note that assuming that both programs have (or both do not have) earmarked funds to acquire the primary resource yields trivial situations where there is no requirement for resource transfer. In Section 4 we will relax this assumption when we consider the case of divisible goods.

In this section, we assume that the probability of an adverse event requiring assistance from program i only is given by q_i, and the probability that both programs have to provide disaster relief is given by q_{AB}. Hence, the probability that program A needs to provide disaster relief is given by $p_A = q_A + q_{AB}$, and the probability that program B needs to provide disaster relief is given by $p_B = q_B + q_{AB}$. This formulation models that the demand for both programs could be correlated, and has a coefficient of correlation $\rho = \frac{q_{AB} - p_A p_B}{\sqrt{p_A p_B (1-p_A)(1-p_B)}}$.

We begin by describing the first case, in which transfer of the primary resource between the programs is not allowed.

3.1.1. Primary Resource Nontransferable. Since, Program A has the required earmarked funding to purchase the primary resource, its net surplus is $u_A(x_A)p_A - x_A - c$, where x_A is its infrastructure investment. Program A's problem is given by

$$\max_{x_A \geq 0} u_A(x_A)p_A - x_A - c.$$

From the first-order conditions, Program A should make the up-front infrastructural investment given by $\frac{du_A(x_A)}{dx_A} = 1/p_A$, let $\tilde{x}_A$ be the solution to A's problem that satisfies this equation. We compute the net social welfare in this case, which is equal to the combined utility surplus of the two programs. Since Program B does not have the required funding to procure the primary resource and in this case transfer of the resource from A to B is not allowed, Program B will not make any infrastructure investment. Therefore, the joint utility in this case is $\Pi_1 = u_A(\tilde{x}_A)p_A - \tilde{x}_A - c$ as the net utility of Program B is zero; here Π_1 denotes the net social welfare in Case 1.

Admittedly, this is an artificial case we include to facilitate a comparison of different transfer mechanisms studied in this paper. In practice, transfers are mostly feasible but may require long and tedious procedures to obtain donor agreement. Note that in emergency situations, these long lead times are quasi-equivalent to non-allowed resource transfers since the relief would come too late anyway.

3.1.2. Primary Resource Transferable If Not Utilized by Acquirer. In this case, Program A has the option to transfer the primary resource to Program B if it does not require the resource and Program B does. Note that in this case both programs make infrastructural investments for using the primary resource, even though only Program A has guaranteed access to it (Habib and Johnsen 1999). The program that owns the primary resource has the first right of use, but the resource can be transferred if this program does not actually need to utilize it.

Since the primary resource is procured using earmarked donations, in case of a transfer the donor program must be adequately compensated to maintain the constraints levied by earmarking.

Therefore, it is important to determine the transfer price between the programs to analyze this case. A general way to determine the transfer price of the primary resource is to use the Generalized Nash bargaining (GNB) framework. Under the GNB framework, if Program B needs to use the primary resource but Program A does not (this event has a probability of q_B), the ex-post expected Generalized Nash bargaining surplus is given by $[u_B(x_B) - p_T]^{1-\beta} p_T^{\beta}$, where p_T is the transfer price and the bargaining power of Program B is $(1-\beta)$ and that of Program A is β. Note that A's surplus does not include its investments in the primary resource and infrastructure, since they are sunk. Maximizing the bargaining surplus results in the transfer price of $p_T = \beta u_B(x_B)$. Hence, under the GNB framework, if the primary resource is transferred by Program A to Program B, the surplus accruing to Program B is given by $u_B(x_B) - p_T = (1-\beta)u_B(x_B)$ and the surplus for Program A is given by $p_T = \beta u_B(x_B)$.

We next characterize the infrastructure-specific investments of both aid programs.

Using the transfer price p_T, Program A solves the following problem to determine its infrastructure investment,

$$\max_{x_A \geq 0} u_A(x_A) p_A + \beta u_B(x_B) q_B - x_A - c.$$

It is clear that $\tilde{x}_A$ solves Program A's problem, where $\tilde{x}_A$ is as in Section 3.1.1. Program B's problem is

$$\max_{x_B \geq 0} (1-\beta) u_B(x_B) q_B - x_B.$$

From the first-order conditions, Program B should make the infrastructural investment given by $(1-\beta)\frac{du_B(x_B)}{dx_B} = 1/q_B$. Let $\hat{x}_B$ be the solution to Program B's problem. The joint utility in this case is $\Pi_2 = u_A(\tilde{x}_A)p_A + u_B(\hat{x}_B)q_B - \hat{x}_B - \tilde{x}_A - c$, where Π_2 denotes the net social welfare in Case 2. We now compare the net social welfare in Case 2 with that in Case 1.

Proposition 1: *The net social welfare when the primary resource is transferable is greater than when it is not transferable; that is,* $\Pi_2 > \Pi_1$.

Proposition 1 is of interest because it confirms that the flexibility of transferring primary resource ensures greater welfare for both programs—even though the assets cannot be jointly owned and one of the programs does not have the funding to acquire the primary resource. Observe that investing in the primary resource does not directly add utility to either program; rather, the flexibility of having the primary resource to justify up-front infrastructural investments yields a higher utility for Program B, which can now provide services should an adverse event occur within its territory.

However, Program A also benefits from that flexibility because it can count as a surplus the funds that it earns from the transfer when it does not utilize the resource.

Next, we analyze the case of a central entity that can buy the primary resource from Program A if it does not need the primary resource, and sell it to Program B if the latter needs it.

3.1.3. Primary Resources can be Transferred to Central Entity. In this case, the aid program A has the right to transfer its primary resource to a central entity if it does not require the use of the primary resource, and the central entity can sell the primary resource to Program B. As before, both programs make respective up-front infrastructural investments of x_A and x_B. If Program A sells the primary resource it has acquired to the central entity, then the central entity pays Program A with a fee of p_C, and if the central entity sells the primary resource to Program B, then Program B pays a fee of p_S to the central entity. If A utilizes the resource, then there are no transactions with the central entity. Program A's problem of determining its optimal infrastructural investment may be written as

$$\max_{x_A \geq 0} u_A(x_A)p_A + p_C(1 - p_A) - x_A.$$

It follows easily that $\tilde{x}_A$ is the solution to Program A's problem. Program B's problem is

$$\max_{x_B \geq 0} (u_B(x_B) - p_S)q_B - x_B.$$

Let $\bar{x}_B$ be the solution to B's problem; that solution is characterized by $\frac{du_B(x_B)}{dx_B} = 1/q_B$. The joint utility in this case is $\Pi_3 = u_A(\tilde{x}_A)p_A + u_B(\bar{x}_B)q_B - \tilde{x}_A - \bar{x}_B - c$, which is the net social welfare of the entire system in Case 3 (i.e., the combined utilities of A and B and of the central entity, too). We now compare the net social welfare generated in this case with that in Case 2.

Proposition 2: *The net social welfare when the primary resource is transferable between two programs (Case 2) is less than when a central entity can acquire the primary resource from one program and then sell it to the other program (Case 3); that is,* $\Pi_3 > \Pi_2$. *Program A makes the same infrastructural investment in Cases 2 and 3, whereas Program B makes a greater infrastructural investment in Case 3 than in Case 2.*

Proposition 2 shows that the central entity can Pareto-increase the two programs' infrastructural investments to levels that exceed those obtained in Case 2. The central entity has two advantages compared to Case 2 where the two programs mutually agree on a resource transfer mechanism without the involvement of a third-party.

First, the central entity eliminates the loss of efficiency due to the gaming in the system that occurs in Case 2 because of the bargaining process that determines the transfer mechanism between the programs. Second, the central entity increases potentially the utility to Program A from the relief effort by providing a salvage value to it of the primary resource that could be higher than what it would obtain from Program B if Program B needed the primary resource and Program A did not. In Case 2, Program A had to acquire the primary resource up front, and ran the risk that this investment may not have been recouped if the adverse event did not happen. So that the central entity is not transferring the financial burden of the primary resource, it can structure the transfer payments p_S and p_C such that A is left with the same expected utility as in Case 2. Program B could be offered a subsidy to facilitate B's use of the primary resource.

It is most interesting that the central entity increases overall efficiency by extracting efficiency gains from within the system, and these gains can be used (if needed) to subsidize a program's use of the primary resource. Therefore, this design of a humanitarian logistics system Pareto-dominates the flexibility mechanism of Case 2. It is important to note that the efficiency gain in Case 3 is not owed to any additional flexibility in the system — in both cases transfer of primary resource is allowed — however, the gain stems from the design of the transfer process (facilitated via a central entity or via direct transfer between the programs).

Corollary 1: *The transfer payments p_S and p_C can be set in such a way that $v_i^1 < v_i^2 \leq v_i^3$ for $i \in \{A, B\}$, where v_i^j denotes the expected utility of program i under Case j, and the central entity does not have a negative expected surplus.*

We now investigate whether the results of the system with a central entity can be improved.

Proposition 3: *The net social welfare with a system that includes a central entity (Case 3) is equal to that with a completely centralized system that employs the same resource allocation policy and also entails centralized decision making for the infrastructural investments. With the central entity, decentralized decision making in infrastructural investments does not induce any inefficiency.*

Proposition 3 shows that the net social welfare obtained by Case 3 cannot be improved upon, and this bears several interesting implications for the design of humanitarian supply chains. First, the current structure of these supply chains can be maintained (the earmarking and decision-making autonomy constraints do not have to be violated) for the efficiency of the entire supply chain to increase. Second, even if one program does not have donations required to purchase the primary resource, it can still acquire the primary resource (and its relief effort can be subsidized) by the presence of the central entity. Finally, such organizations do exist in practice; if they are empowered to acquire and sell primary resources, then they can perform the supply chain efficiency function by transferring primary resources between the two programs. We now investigate if the design of humanitarian supply chains can be improved if the primary good is divisible. This analysis is conducted to check the robustness of the results and also to relax the assumption that only one program has the donations to procure the primary resource.

3.2. Model Formulation and Analysis for divisible primary goods

In this section, we analyze the three resource transfer mechanisms described above when the primary resource is divisible, e.g. if medicines, tents, or small transportation assets like motorcycles are the primary resource. To keep the analysis consistent with the previous section, we model that the primary resources procured are limited by the earmarked donations available to the two aid programs. Let the primary resources available to Program i from its earmarked resources be denoted as κ_i, and the demand for the primary resources in the case of an adverse event be denoted by D_i, where D_i is assumed to be stochastic. We assume that $E[(D_i - \kappa_i)^+] > 0$, thus reflecting the scarcity of funding faced by aid agencies. As in the previous case, let x_i denote the investment of Program i in its infrastructure. Finally, define the total response of Program i (the minimum of the demand for the primary resource, and the total quantity of the primary resource it has) if it needs to provide relief be given by r_i. Note that r_i includes the primary resources that Program i has acquired with its earmarked donations, and any transfer of primary resources from the other program. We make an additional assumption in this section.

Assumption 5:The utility of Program i, $u_i(x_i, r_i)$ is jointly concave and increasing in x_i and r_i, where x_i and r_i are complementary.

Assumption 5 ensures that a higher response to an adverse event yields a higher utility, and a higher investment in infrastructure yields a higher utility; and the total response and the infrastructure cannot act as substitutes. Our results for the case where the primary resource is divisible apply to all demand structures of the aid programs irrespective of their inter-relationship (correlated demand or independent demand).

We begin by describing the first case, in which the aid programs (A and B) make their decisions to acquire the primary resource independently and neither program is allowed to transfer that resource.

3.2.1. Primary Resource Nontransferable. Let $\tilde{r}_i$ denote the total response of Program i if an adverse event occurs. Since the primary resources are non-transferable in this case, the net response of Programs A and B are given by $\tilde{r}_A = \min(D_A, \kappa_A)$ and $\tilde{r}_B = \min(D_B, \kappa_B)$ respectively.

If the net utility surplus of the two programs are given by $\tilde{U}_i$, the problems of Programs A and B are given by:

$$\tilde{U}_A = \max_{x_A \geq 0} E[u_A(x_A, \tilde{r}_A)] - x_A$$

$$\tilde{U}_B = \max_{x_B \geq 0} E[u_B(x_B, \tilde{r}_B)] - x_B$$

Using the first-order conditions, Programs A and B should make the optimal up-front infrastructural investment $\tilde{x}_A$ and $\tilde{x}_B$ that are given by $\frac{dE[u_A(x_A,\tilde{r}_A)]}{dx_A} = 1$ and $\frac{dE[u_B(x_B,\tilde{r}_B)]}{dx_B} = 1$, where $\tilde{x}_A$ and $\tilde{x}_B$ are the solutions to these two equalities. As before, the net social welfare is equal to the combined utility surplus of the two programs. The joint expected utility in this case is $\Pi_1 = E[u_A(\tilde{x}_A, \tilde{r}_A)] + E[u_B(\tilde{x}_B, \tilde{r}_B)] - \tilde{x}_A - \tilde{x}_B$; here Π_1 denotes the net social welfare in Case 1. Next we derive the net social welfare when both programs are allowed to transfer the excess primary resources that they have to the other program.

3.2.2. Excess Primary Resources Transferable by Aid Programs. In this case, both programs acquire the primary resource based on their earmarked donations, and after the realization of their demand, they are allowed to transfer their excess primary resources if available to the other aid program. As in the previous case, we use the GNB framework to determine the transfer price of the excess primary resources. Given that the bargaining will happen ex-post the demand realization, we start by determining the transfer price at which the two aid programs will transfer the primary resource to the other if they have excess primary resources.

We start by identifying the transfer price at which Program B will transfer its excess resources to Program A. Let the response functions of Programs A and B in this case be denoted by $\hat{r}_A$ and $\hat{r}_B$ respectively. Given that the programs will only transfer their excess primary resources, $\hat{r}_A$ and $\hat{r}_B$ are given by:

$$\hat{r}_A = \min(D_A, \kappa_A) + \min\{(D_A - \kappa_A)^+, (\kappa_B - D_B)^+\}$$

$$\hat{r}_B = \min(D_B, \kappa_B) + \min\{(D_B - \kappa_B)^+, (\kappa_A - D_A)^+\}$$

If Program B transfers its excess primary resources to Program A at a transfer price of p_{BA}, then the gains from the transfer for the two aid programs (A and B respectively) are given by:

$$G_A = u_A(x_A, \hat{r}_A) - u_A(x_A, \tilde{r}_A) - p_{BA} \min\{(D_A - \kappa_A)^+, (\kappa_B - D_B)^+\}$$

$$G_B = p_{BA} \min\{(D_A - \kappa_A)^+, (\kappa_B - D_B)^+\}$$

The gain of Program A from the primary resources transferred from Program B is given by its net utility gain compared to its utility from the previous case (no transfer of primary resources) minus the cost that it pays Program B for the transferred primary resources, and the gain of Program

B is the added revenue it attains from Program A for the transferred primary resources. Using the GNB framework, the two parties solve $\max_{p_{BA}} G_A^{\beta} G_B^{1-\beta}$ to determine the optimal value of p_{BA}. Similarly, if Program A transfers its excess primary resources to Program B the GNB framework is used to determine the transfer price p_{AB}. The values of the transfer prices p_{BA} and p_{AB} are given by:

$$p_{BA} = \frac{(1-\beta)[u_A(x_A,\hat{r}_A) - u_A(x_A,\tilde{r}_A)]}{\min\{(D_A-\kappa_A)^+,(\kappa_B-D_B)^+\}} \text{ if } \min\{(D_A-\kappa_A)^+,(\kappa_B-D_B)^+\} > 0$$

$$p_{AB} = \frac{\beta[u_B(x_B,\hat{r}_B) - u_B(x_B,\tilde{r}_B)]}{\min\{(D_B-\kappa_B)^+,(\kappa_A-D_A)^+\}} \text{ if } \min\{(D_B-\kappa_B)^+,(\kappa_A-D_A)^+\} > 0$$

The net utility surplus $\hat{U}_i$ of the two aid programs are then given by:

$$\hat{U}_A = E[u_A(x_A,\hat{r}_A)] - (1-\beta)E[u_A(x_A,\hat{r}_A) - u_A(x_A,\tilde{r}_A)] + \beta E[u_B(x_B,\hat{r}_B) - u_B(x_B,\tilde{r}_B)] - x_A$$

$$\hat{U}_B = E[u_B(x_B,\hat{r}_B)] - \beta E[u_B(x_B,\hat{r}_B) - u_B(x_B,\tilde{r}_B)] + (1-\beta)E[u_A(x_A,\hat{r}_A) - u_A(x_A,\tilde{r}_A)] - x_B$$

We next characterize the infrastructure-specific investments of both aid programs. Using the first-order conditions for the above expressions yields the optimal infrastructural investments of Programs A and B that are given by $\frac{dE[u_A(x_A,\hat{r}_A)]}{dx_A} - (1-\beta)\frac{dE[u_A(x_A,\hat{r}_A)-u_A(x_A,\tilde{r}_A)]}{dx_A} = 1$, and $\frac{dE[u_B(x_B,\hat{r}_B)]}{dx_B} - \beta\frac{dE[u_B(x_B,\hat{r}_B)-u_B(x_B,\tilde{r}_B)]}{dx_B} = 1$ respectively. Let $\hat{x}_A$ and $\hat{x}_B$ denote the optimal infrastructural investments of the two aid programs.

In this case, $\Pi_2 = \beta E[u_A(x_A,\hat{r}_A)] + (1-\beta)E[u_A(x_A,\tilde{r}_A)] - \hat{x}_A + (1-\beta)E[u_B(x_B,\hat{r}_B)] + \beta E[u_B(x_B,\tilde{r}_B)] - \hat{x}_B$ denotes the net social welfare.

Proposition 4: *The net social welfare with divisible primary resources that are transferable is greater than when the primary resources are not transferable; that is,* $\Pi_2 > \Pi_1$.

Proposition 4 confirms that in the case of divisible primary resources as well, the flexibility of transferring primary resource from one program to the other ensures greater welfare for both programs. In this case, transferring the excess primary resources from one party to the other increases the infrastructural investments and the net utility surplus of both programs, as both programs benefit from the flexibility afforded by the transfer of excess primary resources. Hence, the infrastructural investments for both programs are higher if the primary resource is divisible (in contrast, if the primary resource is indivisible or expensive, as in the previous section, one program made the same infrastructural investment (but got a higher utility), while the other program made a higher infrastructural investment). Also, both programs increase their utility in case a transfer of primary resources is done; the donor program can count as a surplus the funds that it earns from the transfer when it does not utilize the resource, and the program that has acquired the excess primary resources gets a higher utility from the acquisition of more primary resources as it is resource constrained (the aid programs only acquire primary resources when their demand exceeds their available resources). Finally, we analyze the case of a central entity that can purchase excess primary resources from one aid program, and sell them to the other aid program if required.

3.2.3. Primary Resources Transferable to Central Entity. We now analyze the role of the central entity in the case where the primary resources are divisible. As before, both aid programs have the right to sell excess primary resources to the central entity that can then sell them to the other aid program if required. As before, the central entity pays the individual aid programs with a fee of p_C per unit of the excess primary resources acquired, and if required, sells these resources to the other program and charges a fee of p_S per unit of this resource. The total response of Programs A and B in this case are given by $\hat{r}_A$ and $\hat{r}_B$ respectively, which are defined in the same way as in the previous section. The net utility surplus $\bar{U}_i$ of the two aid programs are then given by:

$$\bar{U}_A = E[u_A(x_A, \hat{r}_A)] - p_S E[\min\{(D_A - \kappa_A)^+, (\kappa_B - D_B)^+\}] + p_C(\kappa_A - D_A)^+ - x_A$$

$$\bar{U}_B = E[u_B(x_B, \hat{r}_B)] - p_S E[\min\{(D_B - \kappa_B)^+, (\kappa_A - D_A)^+\}] + p_C(\kappa_B - D_B)^+ - x_B$$

Let $\bar{x}_A$ and $\bar{x}_B$ be the solution to the infrastructure investment problem of the two programs; that solution is characterized by $\frac{dE[u_i(x_i, \hat{r}_i)]}{dx_i} = 1$, where $i = A, B$. We now compare the net social welfare of the entire system in Case 3 (the combined net surplus utilities of A and B and of the central entity) with that in Case 2.

Proposition 5: *The net social welfare when the primary resources are transferable between two programs (Case 2) is less than when the two aid programs can sell their excess resources to a central entity which can sell the acquired primary resources to the other program (Case 3); that is,* $\Pi_3 > \Pi_2$. *The infrastructural investments of the two aid programs are ranked as follows:* $\tilde{x}_i < \hat{x}_i < \bar{x}_i$, *i=A,B. Hence, the infrastructural investments of the two aid programs are the highest in Case 3, and they are higher in Case 2 than in Case 1. The net social welfare in Case 3 and the infrastructural investments of the two programs are equal to that of a completely centralized system that employs the same resource allocation policy and also entails centralized decision making for the infrastructural investments.*

Proposition 5 shows that the central entity can increase the two programs' infrastructural investments to levels that exceed those obtained in Case 2. The central entity has two advantages compared to Case 2 where the two programs mutually agree on a resource transfer mechanism without the involvement of a third-party. First, the central entity eliminates the loss of efficiency due to the gaming in the system that occurs in Case 2 because of the bargaining process that determines the transfer mechanism between the programs. Second, the central entity provides a flexibility source to the two aid programs that acts like both a salvage value and an emergency supplier: the two programs can sell any excess primary resources that are not needed to the central entity, as well as acquire excess primary resources. This enables the two aid programs to invest more in their infrastructural investment as they have a higher amount of primary resources to provide relief if needed. Proposition 5 also shows that the net social welfare obtained by Case 3 cannot be improved upon, and this bears several interesting implications for the design of humanitarian supply chains. Centralized transfer features a number of advantages (e.g., lower coordination costs, less gaming, standardization of equipment and quantity discounts from suppliers), as noted in the literature (Tomasini and Van Wassenhove 2009a). We have shown that such systems have the additional advantage of enabling aid programs to make greater infrastructural investments by relieving those programs of the need for ex-post bargaining for asset transfer.

Interestingly, in this case as well, the central entity increases overall efficiency by extracting efficiency gains from within the system, and these gains can be used (if needed) to subsidize a program's use of the primary resource. Therefore, this design of a humanitarian logistics system Pareto-dominates the flexibility mechanism of Case 2.

Corollary 2: *The transfer prices of the central entity p_S and p_C can be set in such a way that $u_i^1 < u_i^2 \leq u_i^3$ for $i \in \{A, B\}$, where u_i^j denotes the expected utility of program i under Case j, and the central entity does not have a negative expected surplus.*

As mentioned previously, this paper takes into account constraints from our field studies: the existence of earmarked budgets and decentralized decision making. We have shown that the efficiency of humanitarian logistics systems can be improved—while continuing to operate within the restrictions and principles of donors and other authorities—by a central entity empowered to make resource transfer decisions. Note that even with the central entity, individual programs make their own infrastructural investment decisions as well as decisions to sell to and acquire the resource from the central entity. It is interesting to note that several large International Humanitarian Organizations (IHO) have recently moved toward such a system, most notably, the International Federation of Red Cross and Red Crescent Societies.

4. Conclusions, Discussion, and Future Research

Our paper considers the design of a supply chain for humanitarian logistical operations—in terms of resource preparedness, response, and collaboration—from the perspective of two independent aid programs that may need to act in response to future adverse events. We provide policy recommendations for the structural design of humanitarian supply chains, and identify conditions under which (inter-organizational) agencies that facilitate the transfer of resources between different aid organizations or programs make the supply chain more efficient. The paper considers two different kinds of investments: an aid program invests in a primary resource with earmarked funding, one that is necessary for providing aid but in itself provides no other utility, and makes an additional, infrastructural investment whose utility is increasing in the amount invested. A simple example would be vehicles and maintenance facilities with spare parts inventories, and well-trained mechanics. We also model constraints that are widely observed in the field of humanitarian supply chains, but unfortunately often ignored in academic research: aid programs are strapped for the funds needed to acquire expensive primary resources ex-ante, donors frequently provide funding that is earmarked for a specific purpose and, programs maintain autonomy in decision making. In this context, we consider the problem of resource transfer and infrastructural investments that must be made under different supply chain designs and then compare the net social welfare obtained in each of these systems.

We compare three different commonly observed designs of humanitarian supply chains in practice, and consider both discrete (expensive or indivisible) primary resources and continuous (divisible) primary resources. We first consider a system in which the two programs operate independently of each other and without the flexibility to transfer resources—even when one program has no use for an acquired primary resource. This is our benchmark system, e.g., one organization may be desperately short of vehicles whereas another may have lots of idle vehicles in the same region. We then contrast the net social welfare obtained if instead the two programs were allowed to transfer resources among themselves should the need arise. We show that flexibility in primary resource transfers increases the system's net social welfare. Finally, with respect to designing the logistics of a system for delivering humanitarian aid, we demonstrate that a central entity fulfills two roles: it eliminates gaming between the aid programs; and it provides an efficient interface for transferring assets from one program to another.

As mentioned above, some IHO have recently moved or are seriously considering moving to such a system. Needless to say, these change projects often encounter considerable cultural and political hurdles since they tend to go against deeply ingrained habits in very decentralized organizations with multiple donors, poor management information systems, and frequently characterized by a lack of transparency and trust. Clearly, coordination also comes at a cost, which we chose not to include here. There may be a cost of setting up collaborations that usually resembles a fixed cost owing to the setting up of relationships between partners (Kelly et al. 2002), and a cost of managing collaborations that resembles a variable transaction cost based on the activities that are being collaborated upon (Kumar and Van Dissel 1996). However, these implementation issues are the subject of further research. It is also interesting to note that several initiatives are underway to create inter-organizational platforms for centralized procurement of expensive assets as suggested by our results. Given the even larger challenges when trying to create these structures across organizations, time will tell if they will indeed appear soon. Our guess would be that a higher frequency of disasters, reduced funding, and increased pressure for more effective use of donor money will indeed accelerate these developments.

The contribution of this paper is twofold. First, the development of our model is based on observations of humanitarian supply chains in practice—that is, while considering the constraints under which these systems operate. Given that aid programs must make up-front investments in different types of resources that may or may not be used, improving the design of such systems under these constraints should increase the efficiency of usage of donor funding. Second, we show that systems with central entities offer efficiency gains over systems that rely on transfer mechanisms between programs. The central entity plays an important role in all three dimensions (i.e., preparedness, response, and collaboration) because it enables humanitarian logistics operations to incorporate them more easily into their resource procurement and allocation functions. This is in stark contrast to supply chains in the private sector, for whom profit is the primary objective. Although some corporate supply chains benefit from coordination imposed by a third party, the central entity described in Case 3 of this paper is more efficient in that it can use its accrued surplus to subsidize programs in need, thereby increasing net social welfare.

In the early phase of this research, we have identified a number of issues that should be addressed in future studies. First, while it is plausible that some funds of the aid program may be open-ended and other funds may be earmarked, for the ease of exposition, we considered all funds to be earmarked. Future research should investigate the impact of a mix of earmarked and open-ended funds. Second, future research should also consider the recourse option for aid programs, where they can request donors for alternate usage of existing earmarked funds. Third, aid programs typically operate under budget constraints for infrastructural investments as well. Incorporating such constraints in the current model would lead to obvious results as the infrastructural investments would either be characterized by the interior point solutions identified in this paper, or by the budget constraint. However, an interesting extension of this paper would be the combination of the budget constraint with the recourse option on earmarked funding. Finally, an important issue that has not been addressed in this paper is the competition between aid programs for donor funding, and the associated change in donor behavior from such a competitive interaction between the aid programs. Future research should consider the impact of these factors on the design of humanitarian supply chains.

To summarize, our paper represents an early effort in the field of humanitarian supply chain design. Our results yield normative policy recommendations for improving the design of humanitarian supply chains. These findings strongly suggest that partners in the design of such systems could make better decisions than heretofore concerning the structures used for resource transfer, and the framework proposed in this paper can serve as a prescriptive model in that regard.

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Appendix

Proof of Proposition 1: $u_A(x_A)p_A - x_A - c$ is concave, as $u_A(x_A)$ is strictly concave by assumption. Hence, the first-order condition for the infrastructural investment x_A gives the optimal value of $\tilde{x}_A$, where $u'_A(\tilde{x}_A) = 1/p_A$. Therefore, $\Pi_1 = u_A(\tilde{x}_A)p_A - \tilde{x}_A - c$. If the primary resource is transferable (Case 2), Program A's optimal investment is $\tilde{x}_A$, which is the same as Case 1. In the generalized Nash bargaining framework, the two parties solve: $\max_{p_T}[u_B(x_B) - p_T]^{1-\beta}p_T^{\beta}$. This yields $p_T = \beta u_B(x_B)$. Program B's optimal infrastructural investment $(\hat{x}_B)$ is given by: $(1-\beta)u_B^{'}(\hat{x}_B) = \frac{1}{q_B}$.

The joint utility in this case is $\Pi_2 = u_A(\tilde{x}_A)p_A - \tilde{x}_A - c + u_B(\hat{x}_B)q_B - \hat{x}_B > u_A(\tilde{x}_A)p_A - \tilde{x}_A - c = \Pi_1$.

Proof of Proposition 2: In Case 3, Program A's optimal investment is $\tilde{x}_A$, which is the same as Case 1 and 2. Program B's optimal investment $\bar{x}_B$ is characterized by $u_B^{'}(\bar{x}_B) = \frac{1}{q_B}$. Since $u_B(\cdot)$ is an increasing concave function, $\bar{x}_B > \hat{x}_B$. The joint utility in this case is $\Pi_3 = u_A(\tilde{x}_A)p_A + u_B(\bar{x}_B)q_B - \tilde{x}_A - \bar{x}_B - c$. Note that by definition of $\hat{x}_B$,

$$\Pi_3 > u_A(\tilde{x}_A)p_A + u_B(\hat{x}_B)q_B - \hat{x}_B - \tilde{x}_A - c = \Pi_2 > \Pi_1.$$

Hence, Case 3 leads to the highest social welfare for the system.

Proof of Corollary 1: Note that $v_A^1 = u_A(\tilde{x}_A)p_A - \tilde{x}_A - c$, $v_A^2 = u_A(\tilde{x}_A)p_A - \tilde{x}_A - c + \beta u_B(\hat{x}_B)q_B > v_A^1$. From Case 3, $v_A^3 = u_A(\tilde{x}_A)p_A - \tilde{x}_A - c + p_C(1-p_A)$. Note that the transfer payment term p_C does not affect the program's investment decision. Set p_C such that $\beta u_B(\hat{x}_B)q_B = p_C(1-p_A)$. Therefore, we have $v_A^2 = v_A^3$.

Similarly, $v_B^2 = (1-\beta)u_B(\hat{x}_B)q_B - \hat{x}_B > 0 = v_B^1$. For Case 3, $v_B^3 = u_B(\bar{x}_B)q_B - \bar{x}_B - p_S q_B$. Set p_S such that $(1-\beta)u_B(\hat{x}_B)q_B - \hat{x}_B = u_B(\bar{x}_B)q_B - \bar{x}_B - p_S q_B$. Therefore, we have $v_B^2 = v_B^3$.

Therefore Case 3 Pareto-dominates Cases 1 and 2. From the central entity's perspective, in the first two cases there is no cost or utility. In Case 3 the surplus of the central entity is $-p_C(1-p_A)+p_Sq_B = -\beta u_B(\hat{x}_B)q_B + u_B(\bar{x}_B)q_B - \bar{x}_B - [(1-\beta)u_B(\hat{x}_B)q_B - \hat{x}_B] = u_B(\bar{x}_B)q_B - \bar{x}_B - [u_B(\hat{x}_B)q_B - \hat{x}_B] > 0$.

Note that the central entity may use this surplus to subsidize the programs by setting p_C and p_S in such a way that $v_i^2 < v_i^3$, as its surplus is strictly positive.

Proof of Proposition 3: In such a centralized system, the total surplus is $u_A(x_A)p_A + u_B(x_B)q_B - x_B - x_A - c$. Therefore the centralized system's investment problem is

$$\Pi_c = \max_{x_A, x_B \geq 0} u_A(x_A)p_A + u_B(x_B)q_B - x_B - x_A - c \ .$$

Note that $\tilde{x}_A$ and $\bar{x}_B$ solve the above maximization problem. Therefore, $\Pi_3 = \Pi_c$.

Proof of Proposition 4: If the excess primary resources are transferred from Program B to Program A, using the Generalized Nash bargaining framework, the two parties solve: $\max_{p_{BA}} G_A^{\beta} G_B^{1-\beta}$, where G_A and G_B are as defined in Section 3.2.2. This yields:

$$\max_{p_{BA}} [u_A(x_A,\hat{r}_A) - u_A(x_A,\tilde{r}_A) - p_{BA}\min{(D_A-\kappa_A)^+, (\kappa_B - D_B)^+}]^{\beta} \times \\ [p_{BA}\min\{(D_A-\kappa_A)^+, (\kappa_B - D_B)^+\}]^{1-\beta}$$

On simplification, this yields: $(1-\beta)[u_A(x_A,\hat{r}_A) - u_A(x_A,\tilde{r}_A)] = p_{BA}\min{(D_A-\kappa_A)^+, (\kappa_B - D_B)^+}$, if $\min{(D_A-\kappa_A)^+, (\kappa_B - D_B)^+} > 0$, which gives us the result

$$p_{BA} = \frac{(1-\beta)[u_A(x_A,\hat{r}_A) - u_A(x_A,\tilde{r}_A)]}{\min\{(D_A-\kappa_A)^+, (\kappa_B - D_B)^+\}}$$

p_{AB} can be shown to be the expression in Section 3.2.2 in a similar manner. Since $\min\{(D_A - \kappa_A)^+, (\kappa_B - D_B)^+\} = 0$ implies that $\hat{r}_A = \tilde{r}_A$, the net utility $\hat{U}_i$ of the two aid programs are then given by:

$$\hat{U}_A = E[u_A(x_A,\hat{r}_A)] - (1-\beta)E[u_A(x_A,\hat{r}_A) - u_A(x_A,\tilde{r}_A)] + \beta E[u_B(x_B,\hat{r}_B) - u_B(x_B,\tilde{r}_B)] - x_A$$

$$\hat{U}_B = E[u_B(x_B,\hat{r}_B)] - \beta E[u_B(x_B,\hat{r}_B) - u_B(x_B,\tilde{r}_B)] + (1-\beta)E[u_A(x_A,\hat{r}_A) - u_A(x_A,\tilde{r}_A)] - x_B$$

The optimal values of the infrastructural investments $\hat{x}_A$ and $\hat{x}_B$ of Programs A and B are given by $\frac{dE[u_A(x_A,\hat{r}_A)]}{dx_A} - (1-\beta)\frac{dE[u_A(x_A,\hat{r}_A) - u_A(x_A,\tilde{r}_A)]}{dx_A} = 1$, and $\frac{dE[u_B(x_B,\hat{r}_B)]}{dx_B} - \beta\frac{dE[u_B(x_B,\hat{r}_B) - u_B(x_B,\tilde{r}_B)]}{dx_B} = 1$

respectively. Note that since $\hat{r}_A \geq \tilde{r}_A$, $E[u_A(x_A, \hat{r}_A)] > E[u_A(x_A, \tilde{r}_A)]$. Since the response and the infrastructure investment are assumed to be complements, $\frac{dE[u_A(x_A,\hat{r}_A)]}{dx_A} > \frac{dE[u_A(x_A,\tilde{r}_A)]}{dx_A}$. Therefore, $\hat{x}_A > \tilde{x}_A$. In a similar vein, $\hat{x}_B > \tilde{x}_B$. All second order conditions are satisfied by our assumption of concavity on the utility functions. The net social welfare of the system is:

$$\Pi_2 = \beta E[u_A(\hat{x}_A, \hat{r}_A)] + (1-\beta)E[u_A(\hat{x}_A, \tilde{r}_A)] - \hat{x}_A + (1-\beta)E[u_B(\hat{x}_B, \hat{r}_B)] + \beta E[u_B(\hat{x}_B, \tilde{r}_B)] - \hat{x}_B$$

Now, $\beta E[u_A(\hat{x}_A, \hat{r}_A)] + (1-\beta)E[u_A(\hat{x}_A, \tilde{r}_A)] - \hat{x}_A > \beta E[u_A(\tilde{x}_A, \hat{r}_A)] + (1-\beta)E[u_A(\tilde{x}_A, \tilde{r}_A)] - \tilde{x}_A$ by definition of $\hat{x}_A$. Also, $\beta E[u_A(\tilde{x}_A, \hat{r}_A)] + (1-\beta)E[u_A(\tilde{x}_A, \tilde{r}_A)] - \tilde{x}_A > \beta E[u_A(\tilde{x}_A, \tilde{r}_A)] + (1-\beta)E[u_A(\tilde{x}_A, \tilde{r}_A)] - \tilde{x}_A = E[u_A(\tilde{x}_A, \tilde{r}_A)] - \tilde{x}_A$. Similarly, $(1-\beta)E[u_B(\hat{x}_B, \hat{r}_B)] + \beta E[u_B(\hat{x}_B, \tilde{r}_B)] - \hat{x}_B > E[u_B(\tilde{x}_B, \tilde{r}_B)] - \tilde{x}_B$. Hence,

$\Pi_2 > E[u_A(\tilde{x}_A, \tilde{r}_A)] + E[u_B(\tilde{x}_B, \tilde{r}_B)] - \tilde{x}_A - \tilde{x}_B = \Pi_1$

Proof of Proposition 5: In Case 3, the infrastructural investment problem of the two aid programs is given by:

$$\bar{U}_A = E[u_A(x_A, \hat{r}_A)] - p_S E[\min\{(D_A - \kappa_A)^+, (\kappa_B - D_B)^+\}] + p_C E[(\kappa_A - D_A)^+] - x_A$$

$$\bar{U}_B = E[u_B(x_B, \hat{r}_B)] - p_S E[\min\{(D_B - \kappa_B)^+, (\kappa_A - D_A)^+\}] + p_C E[(\kappa_B - D_B)^+] - x_B$$

Hence, the optimal investments of the two programs $(\bar{x}_A, \bar{x}_B)$ are characterized by: $\frac{dE[u_A(x_A,\hat{r}_A)]}{dx_A} = 1$ and $\frac{dE[u_B(x_B,\hat{r}_B)]}{dx_B} = 1$ respectively. All second order conditions are satisfied by our assumption of concavity on the utility functions. Since $\frac{dE[u_i(x_i,\hat{r}_i)]}{dx_i} > \frac{dE[u_i(x_i,\tilde{r}_i)]}{dx_i}$ and the utility functions are concave, it follows that $\bar{x}_A > \hat{x}_A$ and $\bar{x}_B > \hat{x}_B$, by their characterizing equations. The problem of the centrally coordinated system is given by:

$\max_{x_A,x_B} E[u_A(x_A, \hat{r}_A) + u_B(x_B, \hat{r}_B)] - x_A - x_B$, as there are no transfer costs in the centrally coordinated system. Let x_A^* and x_B^* denote the optimal infrastructural investments in the centrally coordinated system. The system optimal infrastructural costs x_A^* and x_B^* are characterized by are characterized by: $\frac{dE[u_A(x_A,\hat{r}_A)]}{dx_A} = 1$ and $\frac{dE[u_B(x_B,\hat{r}_B)]}{dx_B} = 1$. Hence, $\bar{x}_A = x_A^*$ and $\bar{x}_B = x_B^*$.

The net social welfare in Case 3 is given by the sum of the utility surplus of the two aid programs and the central entity.

$\Pi_3 = E[u_A(\bar{x}_A, \hat{r}_A)] - \bar{x}_A + E[u_B(\bar{x}_B, \hat{r}_B)] - \bar{x}_B = \Pi_C$, where Π_C is the net social welfare of the centrally coordinated system. From the proof of Proposition 4, the net social surplus in Case 2 is

$$\Pi_2 = \beta E[u_A(\hat{x}_A, \hat{r}_A)] + (1-\beta)E[u_A(\hat{x}_A, \tilde{r}_A)] - \hat{x}_A + (1-\beta)E[u_B(\hat{x}_B, \hat{r}_B)] + \beta E[u_B(\hat{x}_B, \tilde{r}_B)] - \hat{x}_B$$

$= \beta(E[u_A(\hat{x}_A,\hat{r}_A)] - \hat{x}_A + E[u_B(\hat{x}_B,\tilde{r}_B)] - \hat{x}_B) + (1-\beta)(E[u_A(\hat{x}_A,\tilde{r}_A)] - \hat{x}_A + E[u_B(\hat{x}_B,\hat{r}_B)] - \hat{x}_B)$
$< E[u_A(\hat{x}_A,\hat{r}_A)] - \hat{x}_A + E[u_B(\hat{x}_B,\hat{r}_B)] - \hat{x}_B$
$< E[u_A(x^*_A,\hat{r}_A)] - x^*_A + E[u_B(x^*_B,\hat{r}_B)] - x^*_B$
$= \Pi_3$

Proof of Corollary 2: We begin by showing that $u_i^2 > u_i^1$ for $i \in \{A,B\}$. From the proof of Proposition 4 we know that, $u_A^2 = \beta E[u_A(\hat{x}_A,\hat{r}_A)] + (1-\beta)E[u_A(\hat{x}_A,\tilde{r}_A)] - \hat{x}_A > \beta E[u_A(\tilde{x}_A,\hat{r}_A)] + (1-\beta)E[u_A(\tilde{x}_A,\tilde{r}_A)] - \tilde{x}_A > E[u_A(\tilde{x}_A,\tilde{r}_A)] - \tilde{x}_A = u_A^1$.Similarly, $u_B^2 = (1-\beta)E[u_B(\hat{x}_B,\hat{r}_B)] + \beta E[u_B(\hat{x}_B,\tilde{r}_B)] - \hat{x}_B > E[u_B(\tilde{x}_B,\tilde{r}_B)] - \tilde{x}_B = u_B^1$.

We set p_C and p_S such that

$$u_A^2 \le E[u_A(\bar{x}_A,\hat{r}_A)] - p_S E[\min\{(D_A-\kappa_A)^+,(\kappa_B-D_B)^+\}] + p_C E[(\kappa_A - D_A)^+] - \bar{x}_A \qquad (1)$$

$$u_B^2 \le E[u_B(\bar{x}_B,\hat{r}_B)] - p_S E[\min\{(D_B-\kappa_B)^+,(\kappa_A-D_A)^+\}] + p_C E[(\kappa_B - D_B)^+] - \bar{x}_B \qquad (2)$$

Let $\mathcal{X}_i = E[u_i(\bar{x}_i,\hat{r}_i)] - \bar{x}_i - u_i^2$, $\mathcal{T}_A = E[\min\{(D_A-\kappa_A)^+,(\kappa_B-D_B)^+\}]$, $\mathcal{T}_B = E[\min\{(D_B-\kappa_B)^+,(\kappa_A-D_A)^+\}]$, and $\mathcal{Z}_i = E[(\kappa_i - D_i)^+]$. Inequalities (1) and (2) above can be re-written as

$$\mathcal{X}_A - p_S\mathcal{T}_A + p_C\mathcal{Z}_A \ge 0 \qquad (3)$$

$$\mathcal{X}_B - p_S\mathcal{T}_B + p_C\mathcal{Z}_B \ge 0 \qquad (4)$$

Solving these yields the following expressions for p_C and p_S.

$$p_S \le \frac{\mathcal{X}_A + p_C\mathcal{Z}_A}{\mathcal{T}_A} \qquad (5)$$

$$p_S \le \frac{\mathcal{X}_B + p_C\mathcal{Z}_B}{\mathcal{T}_B} \qquad (6)$$

We also need to ensure that the central entity's expected surplus is non-negative. This implies that $U_{CE} = -p_C(\mathcal{Z}_A + \mathcal{Z}_B) + p_S(\mathcal{T}_A + \mathcal{T}_B) \ge 0$. This implies the following inequality

$$p_S \ge p_C\frac{\mathcal{Z}_A + \mathcal{Z}_B}{\mathcal{T}_A + \mathcal{T}_B} \qquad (7)$$

To show that $\exists\{p_S, p_C\}$ that satisfy inequalities (5), (6), and (7) it is sufficient to show that $\exists p_C \ge 0$ such that

$$\frac{\mathcal{X}_A + p_C \mathcal{Z}_A}{\mathcal{T}_A} \geq p_C \frac{\mathcal{Z}_A + \mathcal{Z}_B}{\mathcal{T}_A + \mathcal{T}_B} \tag{8}$$

$$\frac{\mathcal{X}_B + p_C \mathcal{Z}_B}{\mathcal{T}_B} \geq p_C \frac{\mathcal{Z}_A + \mathcal{Z}_B}{\mathcal{T}_A + \mathcal{T}_B} \tag{9}$$

Inequalities (8) and (9) can be re-written as

$$\mathcal{X}_A(\mathcal{T}_A + \mathcal{T}_B) \geq p_C(\mathcal{Z}_B\mathcal{T}_A - \mathcal{Z}_A\mathcal{T}_B) \tag{10}$$

$$\mathcal{X}_B(\mathcal{T}_A + \mathcal{T}_B) \geq p_C(\mathcal{Z}_A\mathcal{T}_B - \mathcal{Z}_B\mathcal{T}_A) \tag{11}$$

If $\mathcal{Z}_B\mathcal{T}_A - \mathcal{Z}_A\mathcal{T}_B < 0$ then Inequality (10) is satisfied for all $p_C \geq 0$ as $\mathcal{X}_A, \mathcal{T}_A, \mathcal{T}_B \geq 0$. In this case $\mathcal{Z}_A\mathcal{T}_B - \mathcal{Z}_B\mathcal{T}_A > 0$, and hence $0 \leq p_C \leq \frac{\mathcal{X}_B(\mathcal{T}_A+\mathcal{T}_B)}{(\mathcal{Z}_A\mathcal{T}_B-\mathcal{Z}_B\mathcal{T}_A)}$ satisfies the sufficient conditions. Similarly, ff $\mathcal{Z}_B\mathcal{T}_A - \mathcal{Z}_A\mathcal{T}_B > 0$ then Inequality (11) is satisfied for all $p_C \geq 0$ as $\mathcal{X}_B, \mathcal{T}_A, \mathcal{T}_B \geq 0$. In this case $0 \leq p_C \leq \frac{\mathcal{X}_A(\mathcal{T}_A+\mathcal{T}_B)}{(\mathcal{Z}_B\mathcal{T}_A-\mathcal{Z}_A\mathcal{T}_B)}$ satisfies the sufficient conditions. Finally, if $\mathcal{Z}_B\mathcal{T}_A - \mathcal{Z}_A\mathcal{T}_B = 0$, then all values of $p_C \geq 0$ satisfy the sufficient conditions. Therefore, $\exists p_S, p_C$ such that $u_i^3 \geq u_i^2$ for $i \in \{A, B\}$ and $U_{CE} \geq 0$.

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